Update of High Ce, High Power HVM LPP-EUV Source Development

Dr. Hakaru Mizoguchi *CTO & Executive Vice President, Gigaphoton*

2013 International Workshop on EUV and Soft X-ray Sources
Dublin, Ireland, 3-7 Nov. 2013

2013.11.05.

GIGAPHOTON

Agenda

- Introduction
- LPP source technologies progress
  - Concept of Gigaphoton LPP source
  - Droplrt generator
  - High CE Pre-pulse
  - Magnetic mitigation technology
  - High Power Laser
  - Corrector Mirror and IR Reduction
  - Extendibility to 1kW EUV power
- Update of LPP source development
  - High power EUV source systems
    - Device #1
    - Device #2
- Summary

Agenda

- Introduction
- LPP source technologies progress
  - Concept of Gigaphoton LPP source
  - Droplrt generator
  - High CE Pre-pulse
  - Magnetic mitigation technology
  - High Power Laser
  - Corrector Mirror and IR Reduction
  - Extendibility to 1kW EUV power
- Update of LPP source development
  - High power EUV source systems
    - Device #1
    - Device #2
- Summary

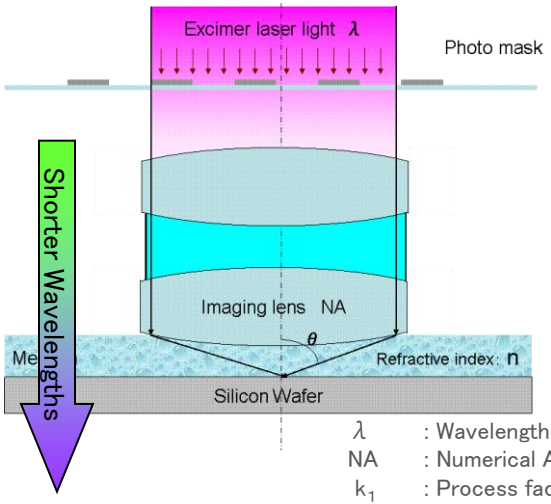
EUV Lithography and light source (1)

Finer patterning is realized by shorter wavelength

$$R = K_1 \frac{\lambda/n}{NA}$$

(*Rayleigh Formula*)

Resolution at projection optic system *R*



λ : Wavelength
NA : Numerical Aperture (NA=sin θ)
k_1 : Process factor
n : Refractive index

	R (K1=0.4) nm	n	medium	λ /n *nm*	NA	Power
KrF dry	124	1	Air	248	0.8	40
ArF dry	103	1	Air	193	0.75	45
F_2 dry	84	1	N_2	157	0.75	–
ArF immersion	40	1.44	H_2O	134	1.35	90
EUV (λ =13.6nm)	**18**	**1**	**Vacuum**	**13.6**	**0.3**	**>250**
EUV (λ =13.6nm)	9	1	Vacuum	13.6	0.6	>500
EUV (λ = 7.6nm)	4.5	1	Vacuum	7.6	0.6	>1000

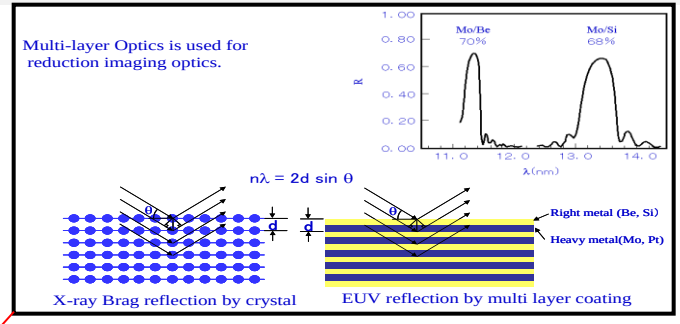
EUV Lithography and light source (2)

Light source issue in EUV lithography

EUV light transmittance is only 2% at 11 refection mirror system

High power light source for HVM exposure tools is the **KEY** Issue

Demand: >**250W** at 1st stage HVM



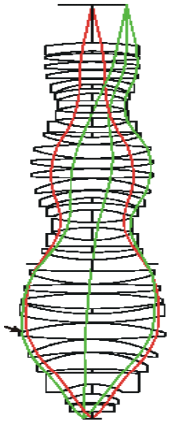
70% Reflection

SiO2,CaF2
>30 lenses and few mirrors

NA=0. 85—1. 35

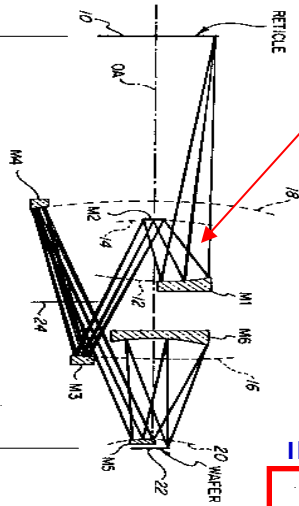
Imaging (30)
$0.98^{30}=0.55$

Imaging (30)
+
Illumination (20)
$0.98^{50}=0.36$



Mask

Wafer



DUV

EUV

Mo/Si multilayer
6-8 mirrors

NA=0. 25—0. 35

Imaging (6)
$0.70^{6}=0.11$

Imaging (6)
+
Illumination + Mask (5)
$0.70^{11}=0.02$

Agenda

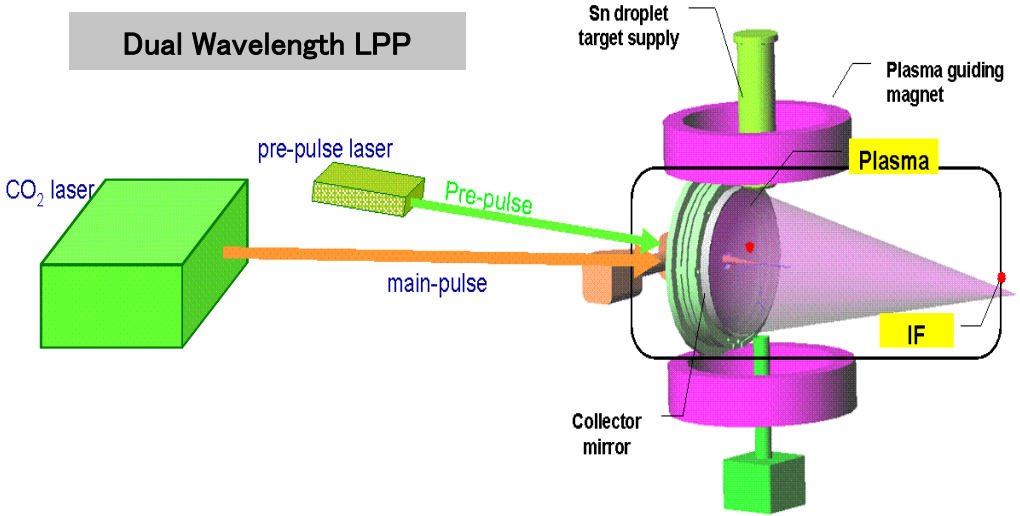
- Introduction
- LPP source technologies progress
  - Concept of Gigaphoton LPP source
  - Droplrt generator
  - High CE Pre-pulse
  - Magnetic mitigation technology
  - High Power Laser
  - Corrector Mirror and IR Reduction
  - Extendibility to 1kW EUV power
- Update of LPP source development
  - High power EUV source systems
    - Device #1
    - Device #2
- Summary

Concept of Gigaphoton LPP Light Source

1. Combined use of Sn droplets & pulsed CO_2 lasers
2. Stable 20mm droplet supply with Droplet Generator (DLG)
3. **Dual wavelength (pre-pulse & main pulse) LPP plasma**
4. Accurate shooting control with droplet and laser beam control
5. **Perfect ionization and magnetic plasma mitigation**

Dual Wavelength LPP

Magnetic Plasma Mitigation



Pre-pulse & Magnetic Mitigation Technology

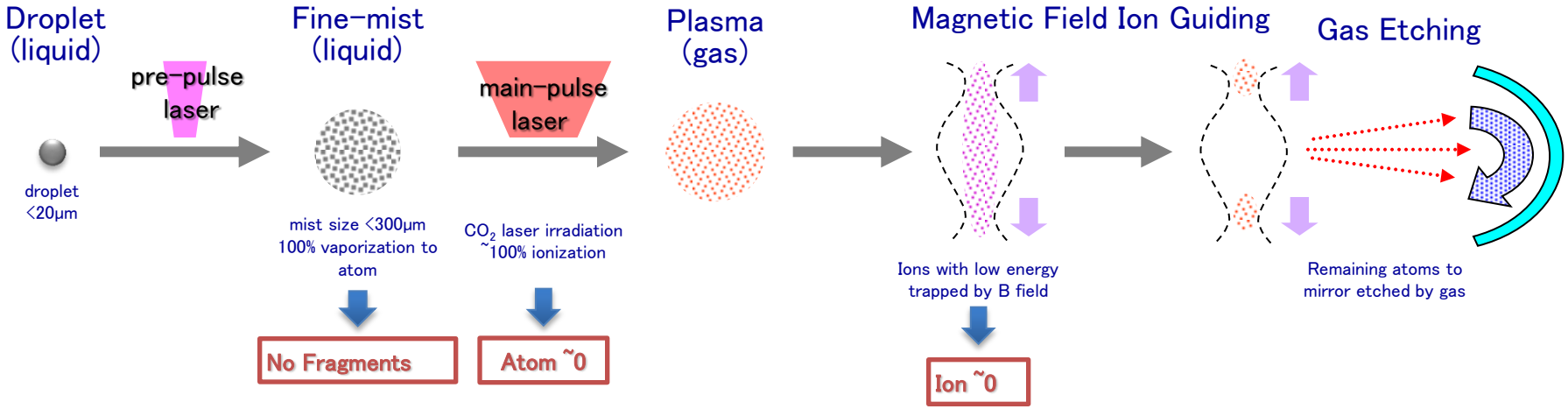
Ideal concept for High Power and Minimal Debris, suitable for HVM

Higher CE and Power

- Optimum wavelength to transform droplets into fine mist
- Higher CE achievement with ideal expansion of the fine mist

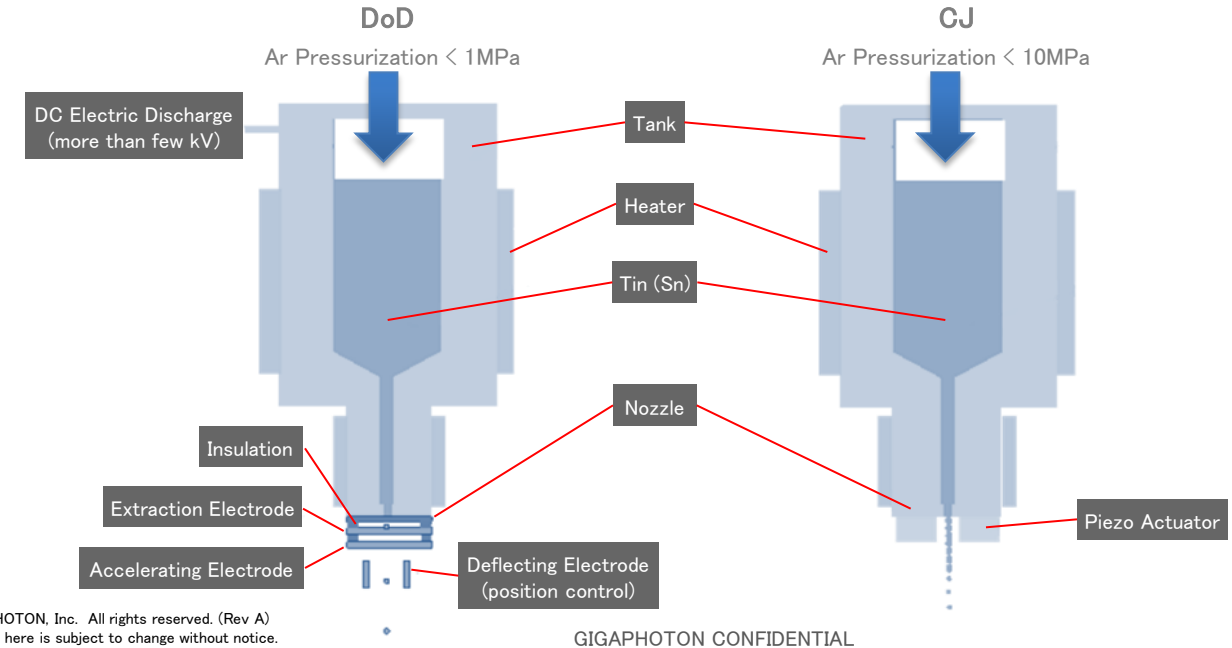
Long Life Chamber

- Debris mitigation by magnetic field
- Ionized tin atoms are guided to tin catcher by magnetic field



Droplet Generator Technology (1)

- GPI is developing two types of tin droplet generators
  - Droplet-on-Demand (DoD) technology is our goal for production tools
  - Continuous Jet (CJ) is for the acceleration of system development except debris mitigation system



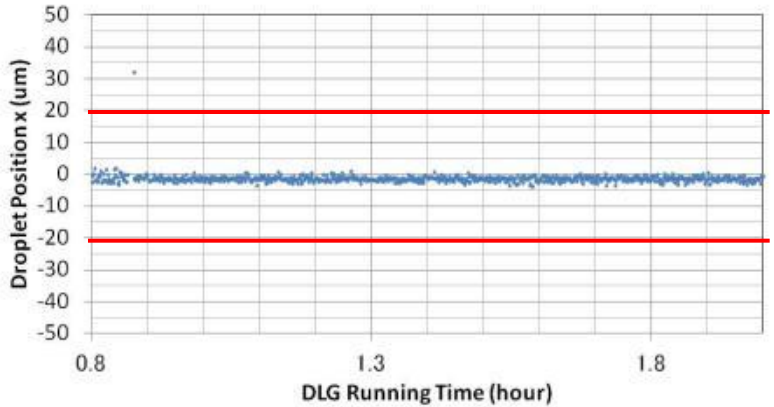
Droplet Generator Technology (2)

Over 70h operation was confirmed

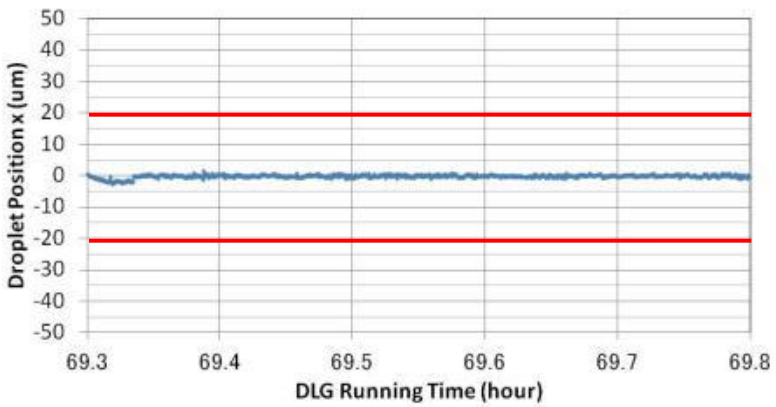
–At Proto system with position control

–No deterioration found after 70h operation

Around 0 hr.

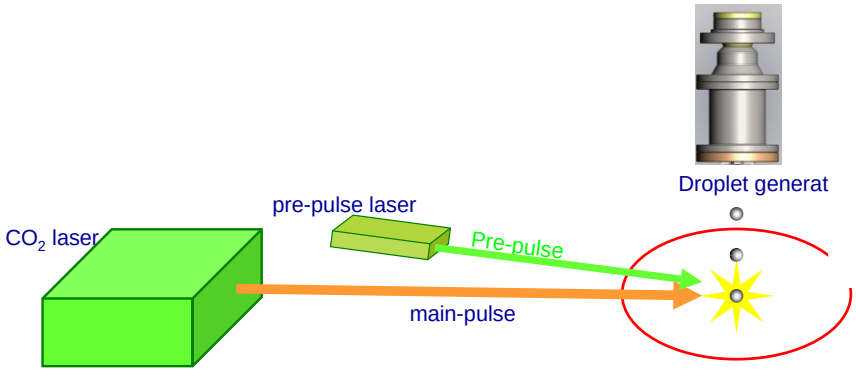


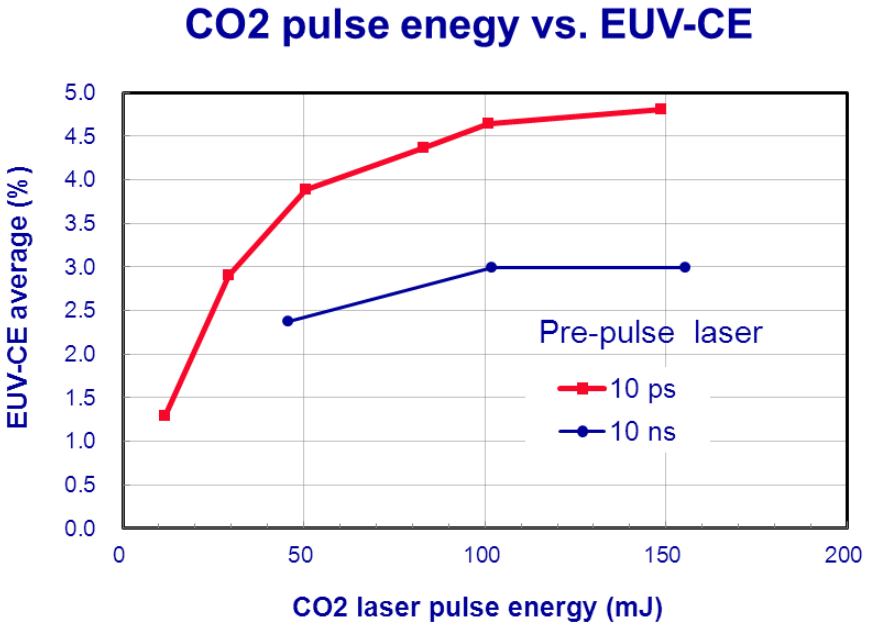
Around 70 hr.



Pre-Pulse technology (1)

- Based on basic physical consideration and experiments, Gigaphoton has chosen to adopt the pre-pulse technology since 2009
- In 2012 Gigaphoton discovered that shortening the pre-pulses duration dramatically enhance the conversion efficiency

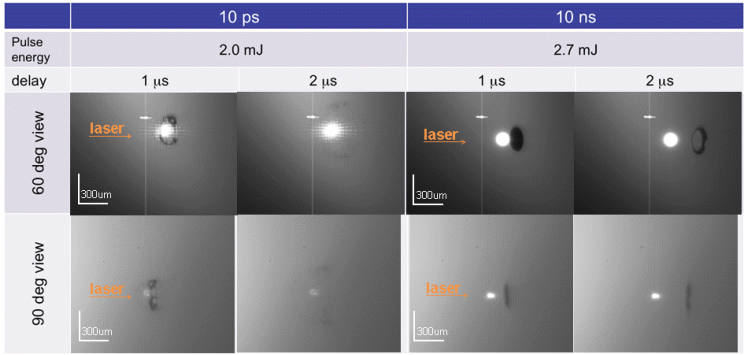


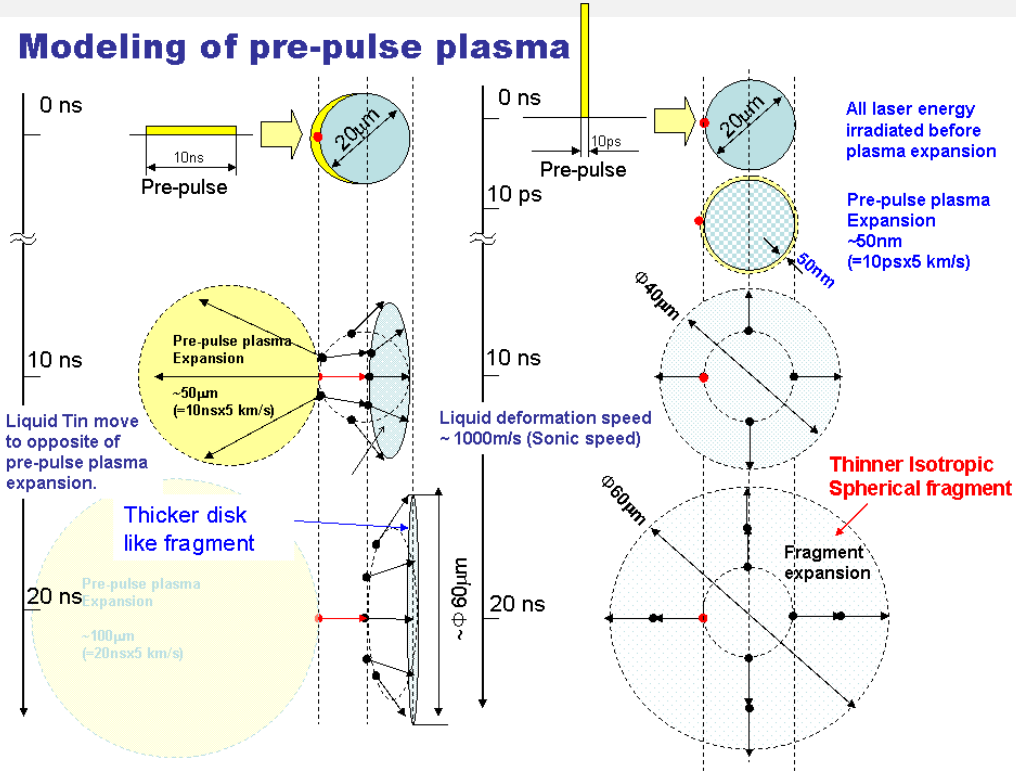


Pre-Pulse Technology (2)

Fragment distribution measurement

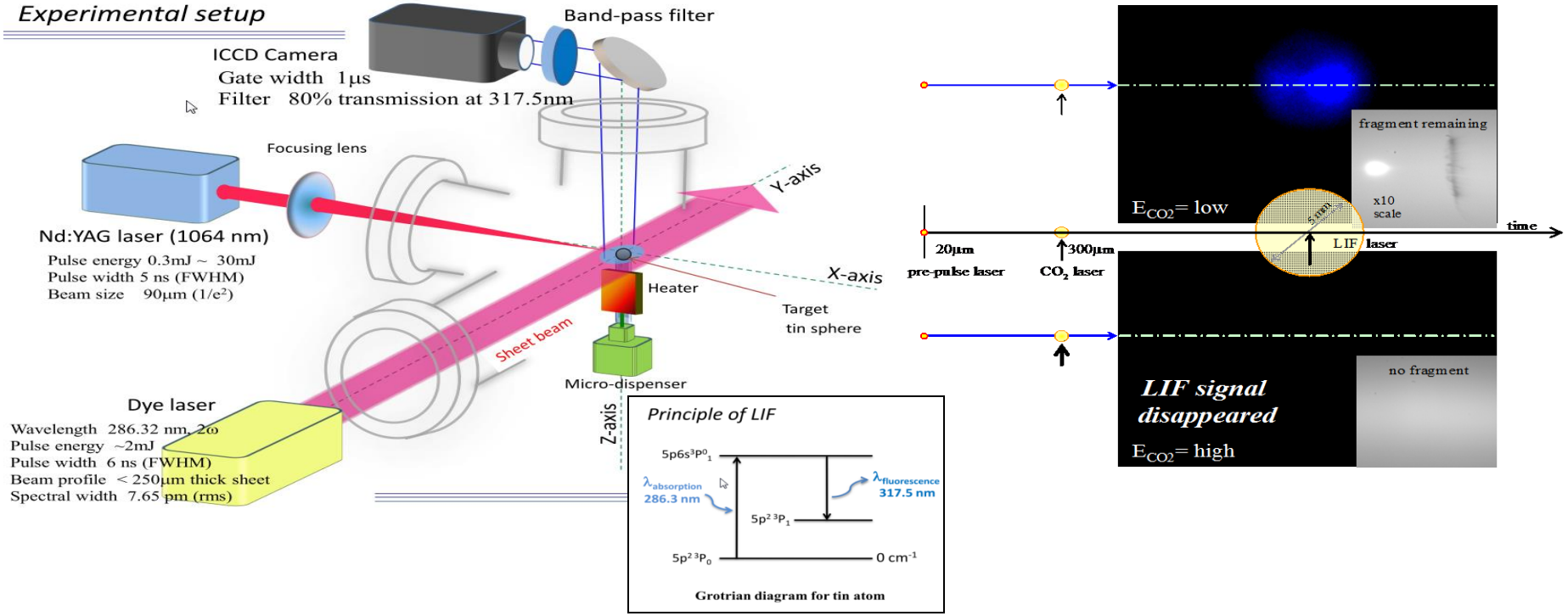
- The mist shape of a picosecond pre-pulse is different from the nanosecond pre-pulse (ps = dome vs. Ns=thin disk or ring)
- Fragment distribution could be a key factor for high CE





Pre-Pulse Technology (3)

Neutral atoms measurement: ionization ratio is investigated

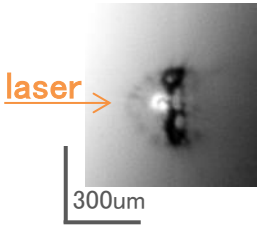


Pre-Pulse Technology (4)

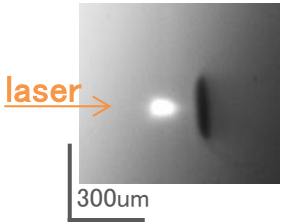
Experiment shows pico-second pre-pulse dramatically enhances ionization rate and CE

Sn Droplet Smash

psec — Dome like target

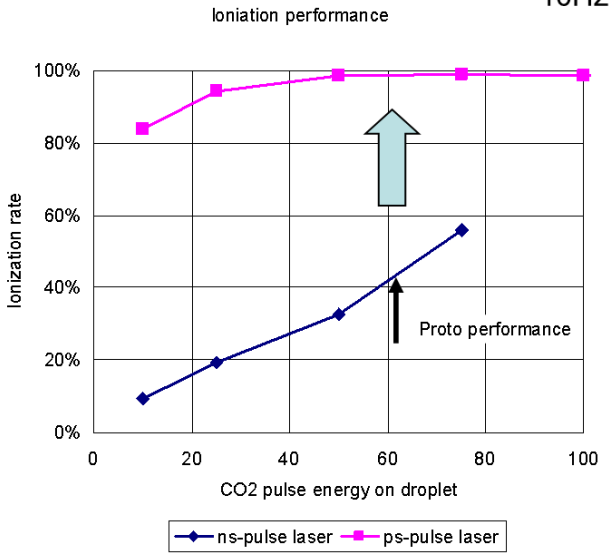


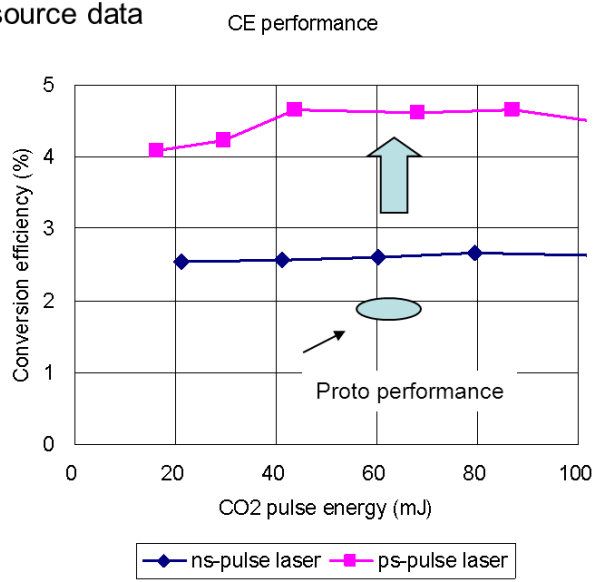
nsec — Flat disk like target



Data in 10Hz Experimental Device

10Hz source data



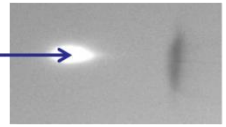


Pre-Pulse Technology (5)

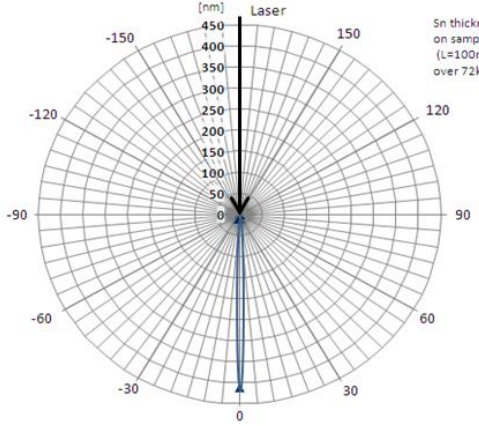
Expanding distribution of Tin mist（10ns vs.10ps）

Remarkable reduction of mist is demonstrated by the pico-second pre-pulse.

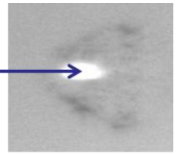
10ns
Pre-pulse



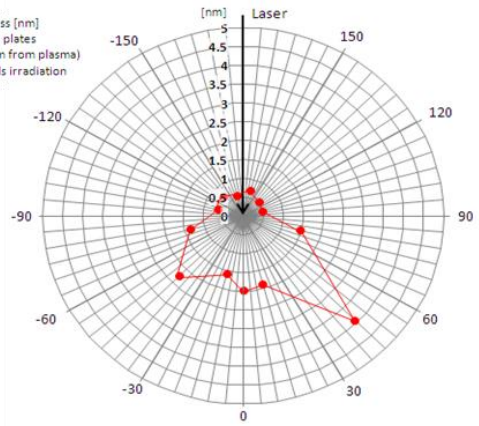
10 ns

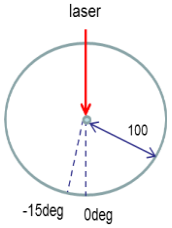


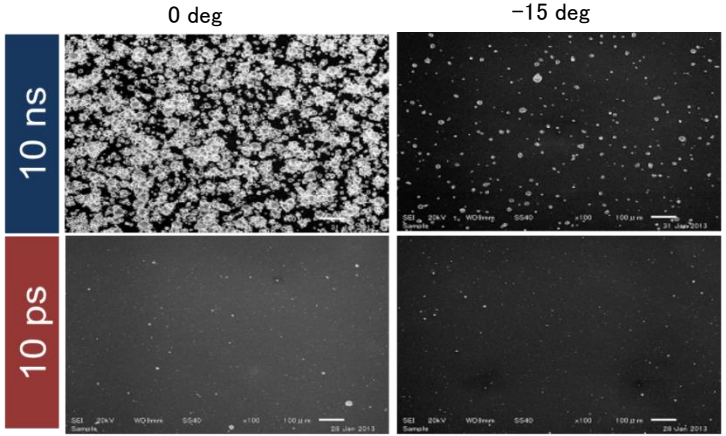
10ps
Pre-pulse



10 ps



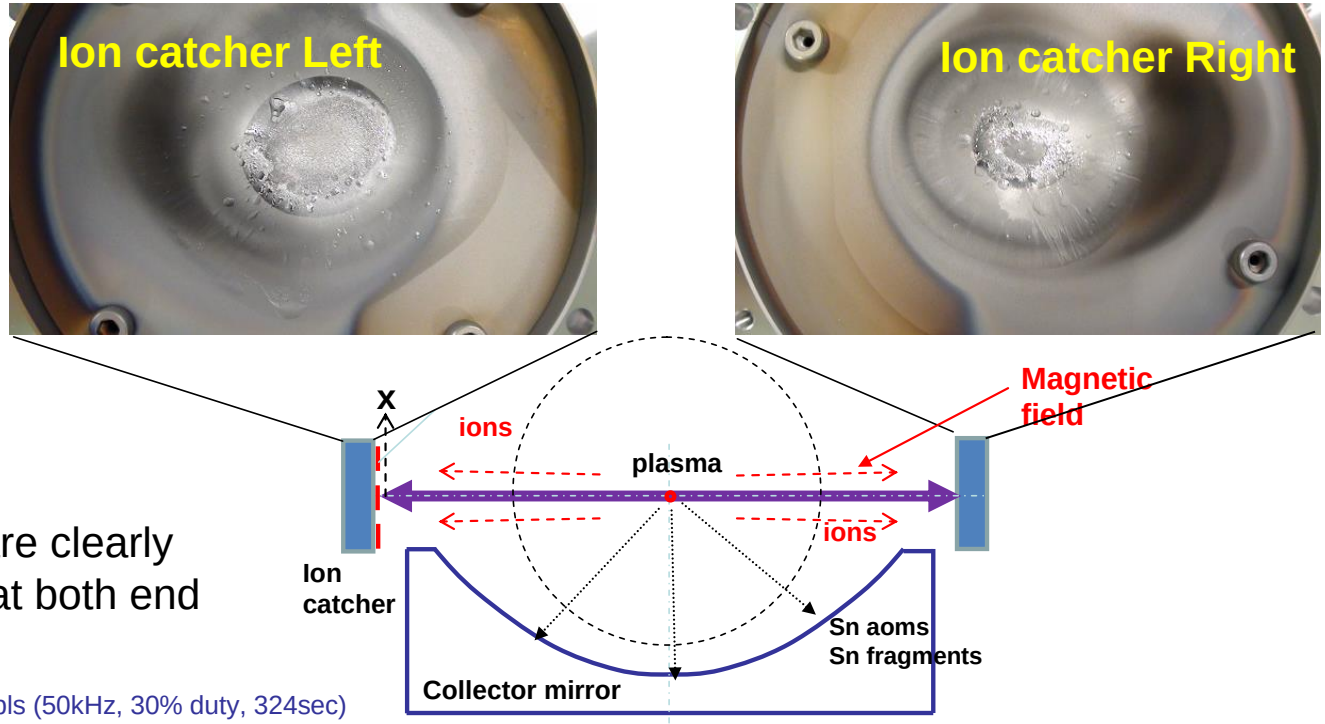




SEM
X100
1280um x 960um

Magnetic Mitigation Technology

Generated ion is corrected at Ion catcher



Magnetically guided ion are clearly corrected by ion catcher at both end of magnetic pole.

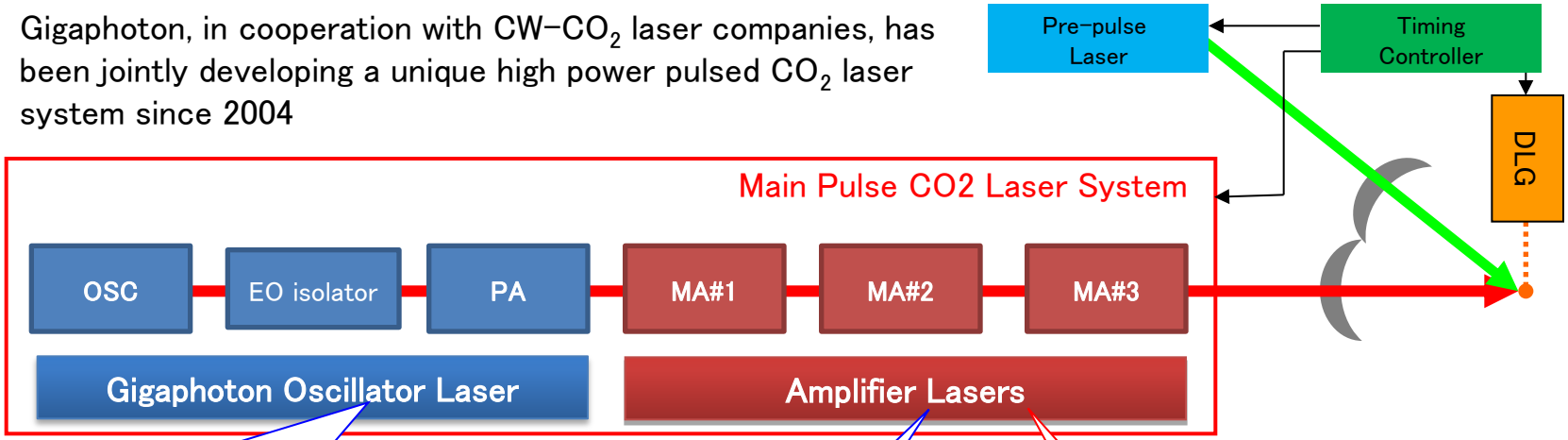
✓4.86Mpls (50kHz, 30% duty, 324sec)

✓Pre-pulse 3.1mJ, CO2 laser 54mJ, DL=ϕ30um,

High Power CO_2 Laser Technology (1)

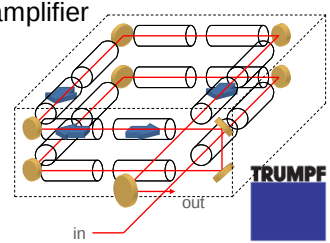
Driver Laser System

Gigaphoton, in cooperation with CW-CO_2 laser companies, has been jointly developing a unique high power pulsed CO_2 laser system since 2004

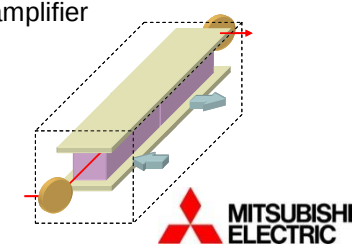


Reported by Dr. Krysztof M Nowak at P-SO-60

Fast axial flow CO2 laser amplifier



Transverse-flow CO2 laser amplifier



High Power CO_2 Laser Technology (2)

Amplifier System A: experiment on present system using Trumpf amplifier laser

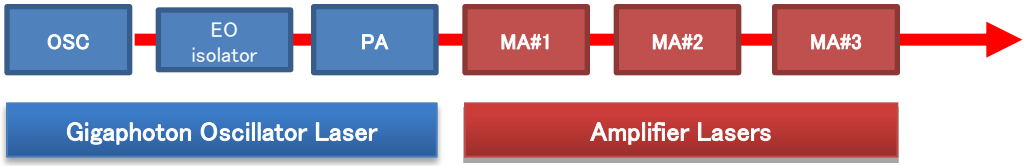
Performance data with 3x MA

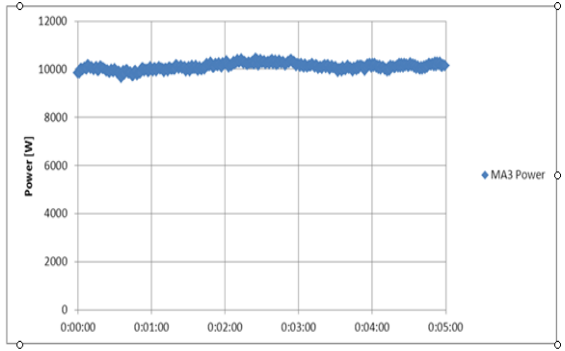
−10kW performance was confirmed during hour level operation

- Pulsed CO2 laser system experiment with Gigaphoton oscillator laser and Trumpf amplifiers x3units laser system.

−Next challenge

- Confirm operation at target shooting
- Further power improvement





High Power CO_2 Laser Technology (3)

Amplifier System B: Laboratory level experiment with Mitsubishi electric amplifier laser

Performance data with 3x MA System-B

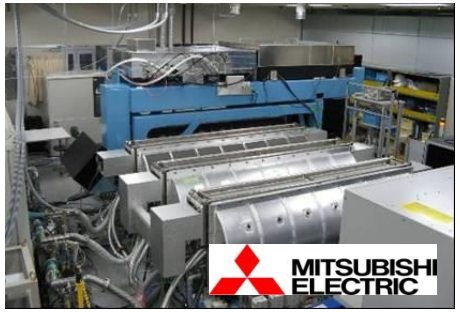
-20kW performance was confirmed at minute level

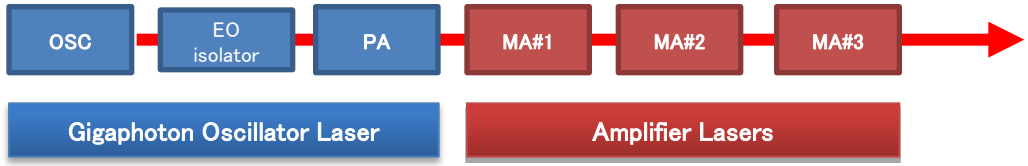
- Pulsed CO_2 laser system experiment with Gigaphoton oscillator laser and 4 Mitsubishi amplifier laser system

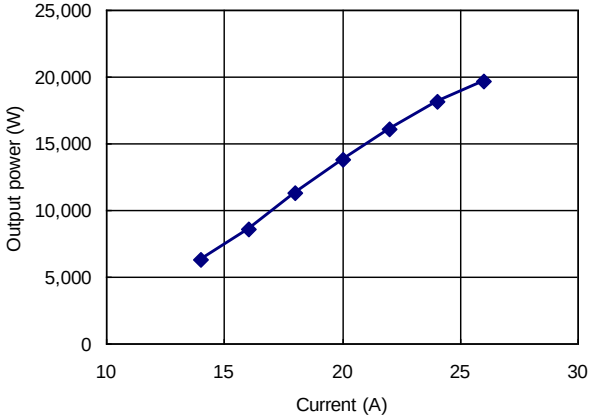
  (Data is reported EUV symposium 2013 in Toyama)

-Next challenge

- Achieve 25kW level
- Field level integration
- Confirm operation while shooting at Sn target







Corrector Mirror and IR Reduction Technology

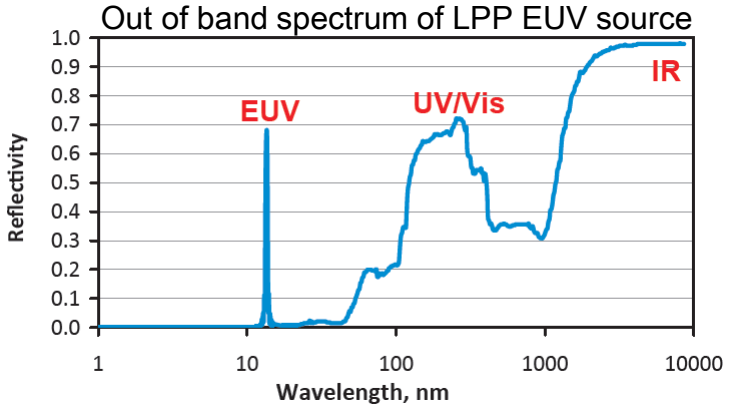
Corrector Mirror Progress

IR Reduction Technology is advancing:

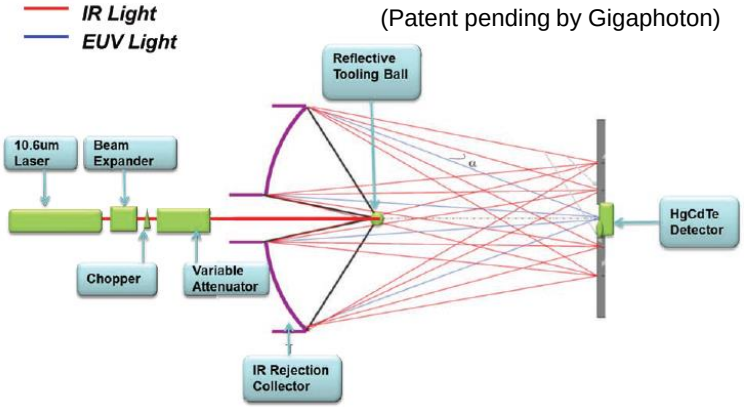
- Gigaphoton is developing IR reduction mirror co-operate with multiple mirror supplier.
- **Rigaku** demonstrated efficient and dramatic IR reduction by grating on the mirror surface- Prefabrication test is completed.

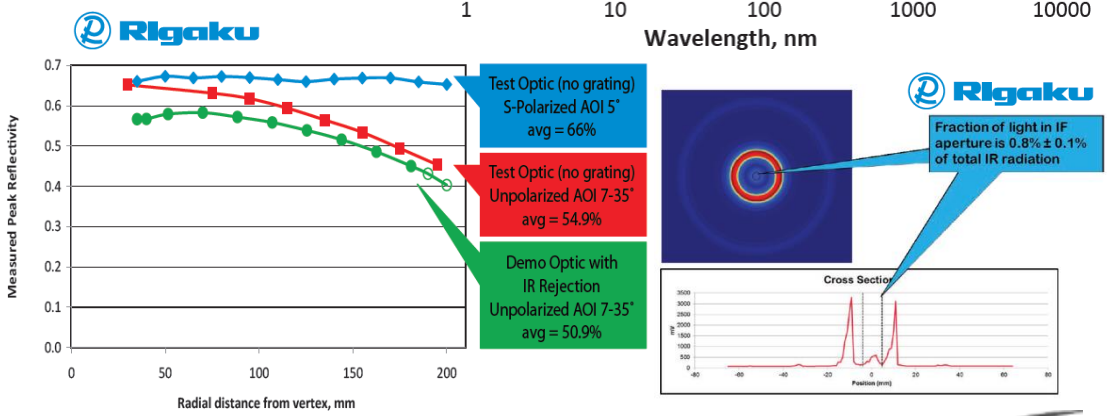
(Data is reported EUV symposium 2013 in Toyama)

- Next step is proto type fabrication and evaluation.



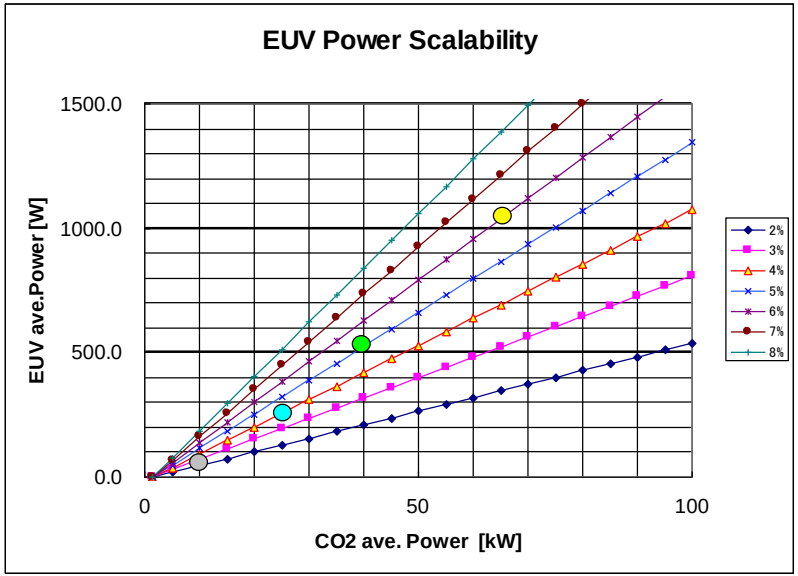
IR Reduction Technology





Extendibility to 1kW EUV Power (1)

Feasibility study of EUV Output Power vs. CO2 Input Power



Feasibility study of extendibility to 1kW

- Conversion efficiency is Key. At least achievement of CE＞4% is essentially important. If not, CO2 laser will become ＞100kW.
- At least ＞50kW CO2 laser power must be realized. Even in best case of CE=8%.
- I believe; 1000W EUV source is feasible in future, from the technical data (experiment of CE and CO2 laser) and technical expectation at present.

Extendibility to 1kW EUV Power (2)

Possible scale up scenario of EUV Output Power vs. CO_2 Input Power

EUV ave.Power[W] @100kHz			Conversion Efficiency [%]						
CO2 laser Energy [mJ]		CO2 laser ave. Power [kW]	2%	3%	4%	5%	6%	7%	8%
	15	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	50	5	19.1	28.7	38.2	47.8	57.3	66.9	76.4
	100	10	46.4	69.6	92.8	116.0	139.2	162.4	185.6
	150	15	73.7	110.6	147.4	184.3	221.1	258.0	294.8
	200	20	101.0	151.5	202.0	252.5	303.0	353.5	404.0
	250	25	128.3	192.5	256.6	320.8	384.9	449.1	513.2
	300	30	155.6	233.4	311.2	389.0	466.8	544.6	622.4
	350	35	182.9	274.4	365.8	457.3	548.7	640.2	731.6
	400	40	210.2	315.3	420.4	525.5	630.6	735.7	840.8
	450	45	237.5	356.3	475.0	593.8	712.5	831.3	950.0
	500	50	264.8	397.2	529.6	662.0	794.4	926.8	1059.2
	550	55	292.1	438.2	584.2	730.3	876.3	1022.4	1168.4
	600	60	319.4	479.1	638.8	798.5	958.2	1117.9	1277.6
	650	65	346.7	520.1	693.4	866.8	1040.1	1213.5	1386.8
	700	70	374.0	561.0	748.0	935.0	1122.0	1309.0	1496.0
	750	75	401.3	602.0	802.6	1003.3	1203.9	1404.6	1605.2
	800	80	428.6	642.9	857.2	1071.5	1285.8	1500.1	1714.4
	850	85	455.9	683.9	911.8	1139.8	1367.7	1595.7	1823.6
	900	90	483.2	724.8	966.4	1208.0	1449.6	1691.2	1932.8
	950	95	510.5	765.8	1021.0	1276.3	1531.5	1786.8	2042.0
	1000	100	537.8	806.7	1075.6	1344.5	1613.4	1882.3	2151.2

Our possible scale-up scenario

	HVM (1st)	HVM (2nd)	HVM(3rd)
EUV power	250W	500W	1000W
CE	4%	5%	6%
Pulse rate	100 kHz	100kHz	100kHz
Pre-pulse laser	Pico-s	Pico-s	Pico-s
CO2 laser power	25kW	40kW	65kW
# of main amps	3	5	8

Agenda

- Introduction
- LPP source technologies progress
  - Concept of Gigaphoton LPP source
  - Droplrt generator
  - High CE Pre-pulse
  - Magnetic mitigation technology
  - High Power Laser
  - Corrector Mirror and IR Reduction
  - Extendibility to 1kW EUV power
- Update of LPP source development
  - High power EUV source systems
    - Device #1
    - Device #2
- Summary

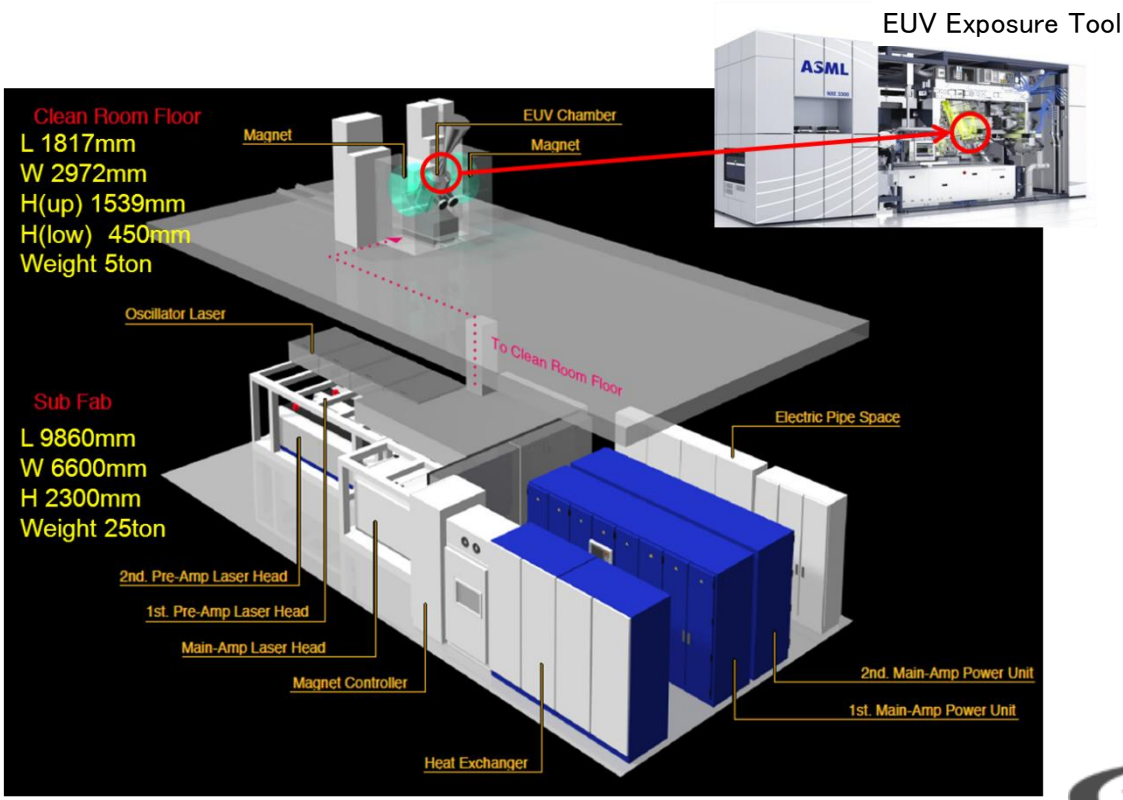
High Power EUV Source Systems (1)

Layout of 250W EUV light source

First HVM EUV Source

- We are developing 250W EUV source.
- Target timing is **2015**

Operational specification (Target)			HVM Source
Performance	EUV Power		> 250W
	CE		> 4.0 %
	Pulse rate		100kHz
	Availability		> 75%
Technology	Droplet generator	Droplet size	< 20mm
	CO2 laser	Power	> 20kW
	Pre-pulse laser	Pulse duration	psec
	Debris mitigation	Magnet, Etching	> 15 days (>1500Mpls)



High Power EUV Source Systems (2)

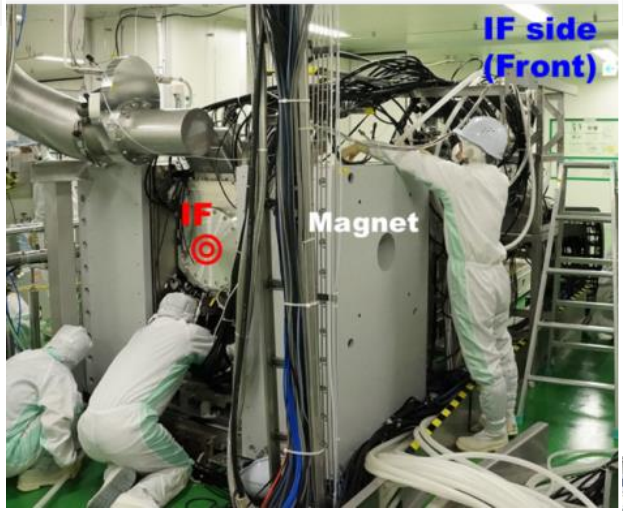
System Specification (Target)

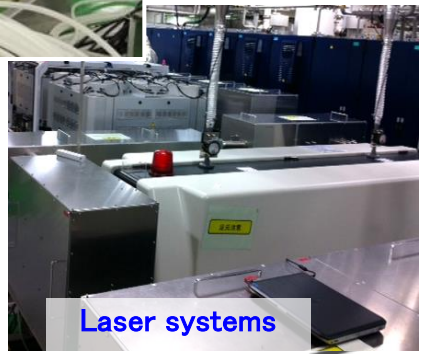
Operational Specification (target)		#1 in PROTO-2	#2 in PROTO-2	PILOT HVM Source
Performance	EUVPower	25W	> 50W	250W
	CE	3 %	4%	4%
	Pulse rate	100kHz	100kHz	100 kHz
	Output angle	horizontal	62 degrees upper (matched to NXE)	62 degrees upper (matched to NXE)
	Availability	1week (operation time)	1week (operation time)	> 75%
Technology	Dloplet generator	20 – 25 μm	20 μm	< 20 μm
	CO2 laser	> 8kW	> 12kW	25kW
	Pre-pulse laser	picosecond	picosecond	picosecond
	Debris mitigation	Validation of magnetic mitigation in system	10days	15days

High Power EUV Source Systems (3)

Status of proto light sources, #1 and #2

- System #1 : For EUV irradiation experiment (Operational)
  - The whole system (lasers and chambers) is working now
  - There are some issues and improvement activity is in progress
- System #2 :For high power development (Under construction)
  - The design and procurement was finished
  - The assembly will be finish soon
  - After the initial adjustment, the first EUV emission will be in this Q4

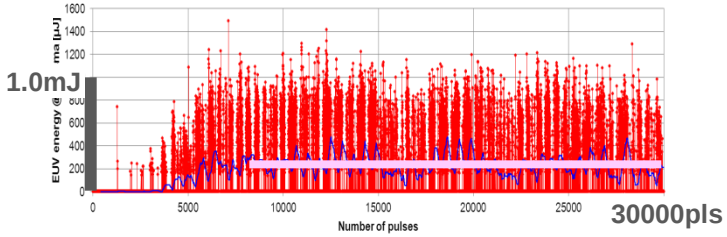




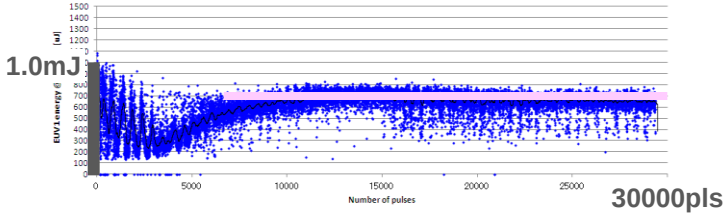
High Power EUV Source Systems (4)

In-burst Power performance improvement at proto #1

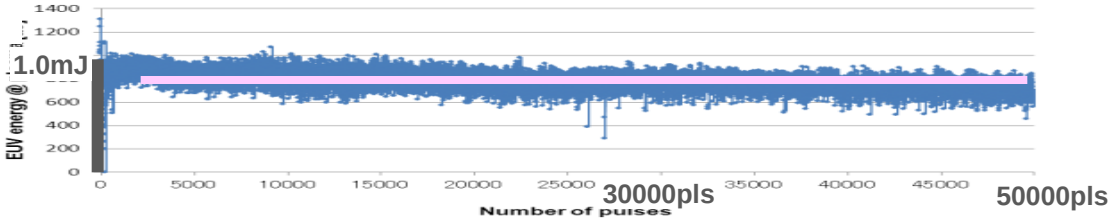
Nov. 2012



Mar. 2012



Aug. 2013



4.3W*, 100kHz
*:EUV Clean power @I/F

Shooting control and stabilization A

6.5W*, 50kHz
*:EUV Clean power @I/F

Shooting control and stabilization B
Improve pre-pulse laser

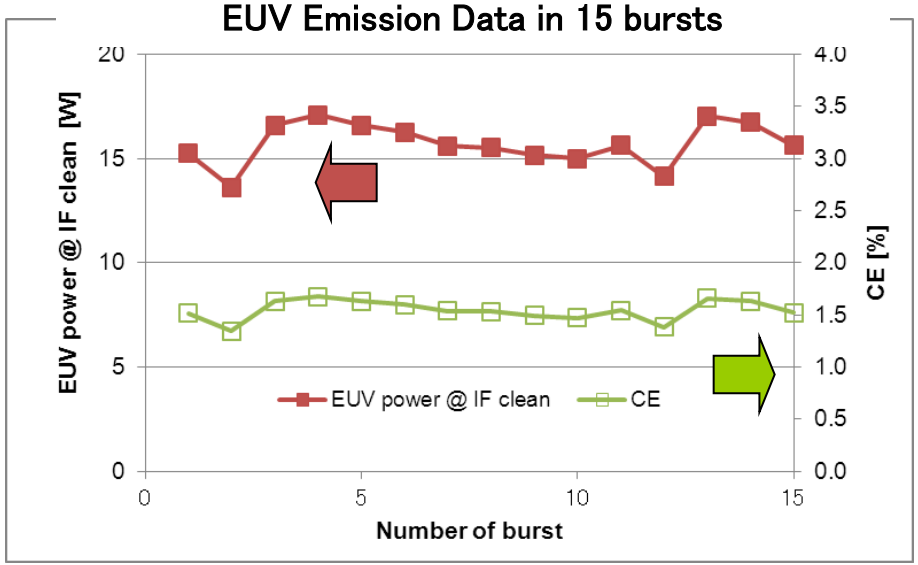
15W*, 100kHz
ON/OFF=0.5s/0.5s
Duty=50%, CE=1.5%
*:EUV Clean power @I/F

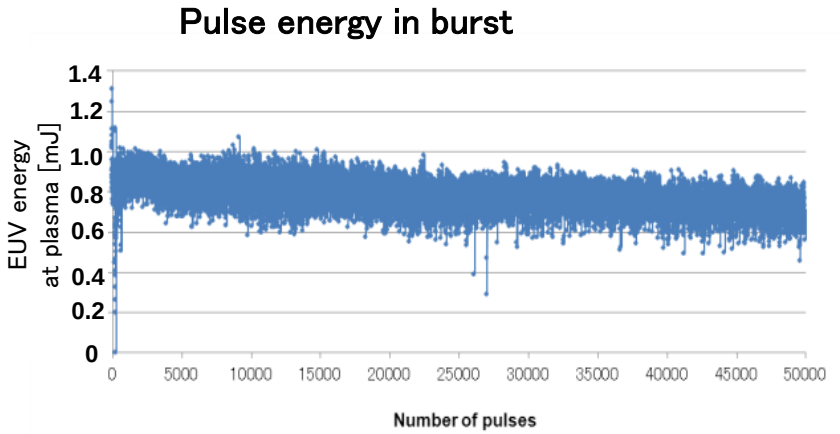
High Power EUV Source Systems (5)

Latest update on power and conversion efficiency (CE)

＊EUV Clean power at I/F[W]

- 15W* (100kHz) EUV power in burst (50% duty) was achieved.
- CE is **1.5%**. Now we are **improving CE >2.5%** by optimizing shooting conditions.
- Higher CE gives high ionization rate to activate magnet mitigation properly.





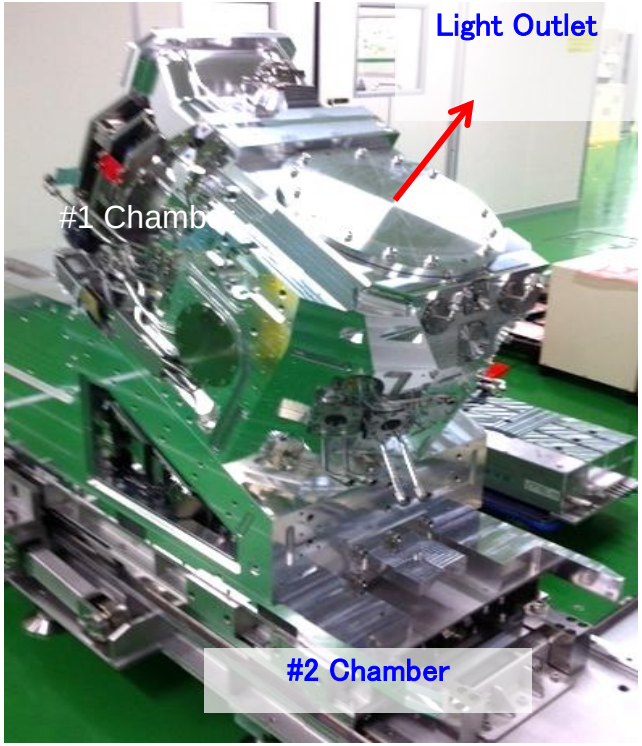
50000pls(0.5sec)ON−0.5secOFF, 50%Duty

High Power EUV Source Systems (6)

Status of proto light sources, #1 and #2

- System #1 : For EUV irradiation experiment (Operational)
  - The whole system (lasers and chambers) is working now
  - There are some issues and improvement activity is in progress

- System #2 :For high power development (Under construction)
  - The design and procurement was finished
  - The assembly will be finish soon
  - After the initial adjustment, the first EUV emission will be in this Q4



Agenda

- Introduction
- LPP source technologies progress
  - Concept of Gigaphoton LPP source
  - Droplrt generator
  - High CE Pre-pulse
  - Magnetic mitigation technology
  - High Power Laser
  - Corrector Mirror and IR Reduction
  - Extendibility to 1kW EUV power
- Update of LPP source development
  - High power EUV source systems
    - Device #1
    - Device #2
- Summary

Summary

- Extendibility of LPP-EUV source power is discussed
  - High CE technology
    - Demonstrated remarkable reduction of mist after the pico-second pre-pulse.
  - Magnetic mitigation is working well in proto-2
  - High power CO2 driver laser technology
    - For >500W EUV source, New 40kW CO2 laser amplifier development project started co-operation with Mitsubishi electric.
    - Target is 25kW until Q1 2013.6　20kW@S/L output is observed after 4-amplifier
  - Progress of corrector mirror and IR reduction technology is reported.
  - Possible scenario of 1000W EUV source is reported
- Gigaphoton LPP source:
  - Droplet generator is improved dramatically, stable operation >100h is demonstrated.
  - CO2 laser achieved 10kW operation with 75% duty.
  - EUV light emission 15 W (@I/F Clean power in 50% duty burst 100kHz) is achieved.
  - Proto-2 #2 is under construction
  - Proto-2 target is 25W level one week operation demonstration by Q4 2013.
- Gigaphoton's shipment target of pilot is 2015.

Acknowledgement

- Thanks for co-operation

  Dr. Akira Endo, Waseda University (Tokyo) & HiLase Project (Prague)
  Prof. Masakazu Washio, Waseda University

  -Thanks for my colleagues in Hiratsuka facility

  Hiroaki Nakarai, Tamotsu Abe, Takeshi Ohta, Krzysztof M Nowak, Yasufumi Kawasuji,
  Hiroshi Tanaka, Yukio Watanabe,Tsukasa Hori, Takeshi Kodama, Yutaka Shiraishi,
  Tatsuya Yanagida,Tsuyoshi Yamada, Taku Yamazaki and Takashi Saitou

- Thanks for technical advice

  Dr. Shinji Okazaki

- Thanks for Cooperation of Mitsubishi electric CO2 laser amplifier development team

- EUV source development funding is partially support by NEDO in JAPAN.

THANK YOU

GIGAPHOTON